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14. ABSTRACT

The purpose of this investigation is to develop an integrated system based on MRI simulation to improve target delineation, target localization and target motion correction for 3-dimensional conformal radiation therapy (3DCRT) and intensity-modulated radiation therapy (IMRT) of prostate cancer. We have performed studies on the effect of intra-fraction prostate motion using MR cine images and we also have been evaluating the accuracy of a stereotactic body frame for patient immobilization using MRI. We have confirmed that treatment planning dose calculations using MRI-derived homogenous geometry are adequate for patient sizes within 38 cm using the gradient distortion correction (GDC) software (Chen et al 2004a 2004b). We have quantified the residual distortions and developed computer software to reduce them using point-by point corrections for large patients (lateral dimension up to 42 cm, (Chen et al 2006)). We have verified dosimetric accuracy and consistency for MR based IMRT treatment planning for prostate cancer using the Monte Carlo method (Chen et al 2007). We have developed a technique to create MR-based digitally reconstructed radiographs (DRR) for patient initial setup for clinical applications of MR-based treatment planning for prostate IMRT (Chen et al 2007).

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Introduction

This project is aimed at exploring MR imaging based treatment planning for radiotherapy of prostate cancer. The specific Aims include (1) to investigate the use of MRI for target delineation, target localization, patient immobilization and prostate motion studies for 3DCRT and IMRT of prostate cancer; (2) to investigate and improve the accuracy of MRI-based treatment planning dose calculation; and (3) to develop practical procedures for the clinical implementation of MRI-based treatment planning for 3DCRT and IMRT of prostate cancer. In the following we describe our work for the project.

Body

In this final report we report on the research accomplishments associated with the tasks outlined in the approved "Statement of Work" between Feb.1, 2004 and Feb. 24 2008.

Task 1. Investigation of target delineation, localization and patient immobilization using MRI

Quantification of the effect of MRI distortion on target delineation and treatment planning dose calculation

During the first year, we have focused on investigating the effect of MRI distortion on target delineation and treatment planning dose calculation. Two papers entitled "MRI-based treatment planning for radiotherapy: Dosimetric verification for prostate IMRT" and "Dosimetric evaluation of MRI-based treatment planning for prostate cancer" were published in Int. J. Radiat. Oncol. Biol. Phys. and Physics in Medicine and Biology, respectively (Chen et al 2004a, 2004b). We summarize the results and conclusions of these studies as follows.

1) We have studied the use of MRI-based treatment planning for prostate cancer and to verify the dosimetry accuracy of its clinical implementation using a commercial treatment planning system. The AcQPlan system Version 5 was used for the study, which is capable of performing dose calculation on both CT and MRI. A four field 3D conformal planning technique was used for the study. First, we verified the dosimetry accuracy of using homogeneous geometry for prostate planning. This was done by calculating dose distributions using the distortion-free CT data with and without heterogeneity correction (equivalent TAR), respectively. As a result, two treatment plans were generated for each patient with the same treatment parameters (i.e., energy, gantry angle, block shape and size, and dose prescription). Second, we evaluated the dosimetry accuracy between CT-based and MRI-based dose calculation. This was achieved by calculating dose distributions using both CT and MRI data without heterogeneity correction (i.e., using homogeneous geometry defined by the patient external contour). The same MUs obtained from CT-based plans were directly used in MRI-based plans so that the effects of residual MRI distortions on external contours and the differences in internal structure volumes between CT and MRI can be quantified. The plans were evaluated based on isodose distributions and dose volume histograms (DVHs) for the target and the critical structures. Based on the DVHs, doses were reported at 95% of the planned treatment volume (PTV), D95, for the prostate, at 35% (D35) and 17% (D17) of the rectum volume, and at 50% (D50) and 25% (D25) of the bladder volume. These dose points were chosen based on our current clinical acceptance criteria for prostate cancer treatments. Our results confirmed that treatment planning

dose calculations using MRI-derived homogenous geometry are adequate for patient sizes within 38 cm after MR image distortion is corrected using the GDC software (Chen et al 2004b).

2) We have investigated the effect of MRI residual distortion after GDC on IMRT treatment planning and dosimetry accuracy. Our results showed that the residual distortion errors are less than 1 cm and will have a negligible clinical impact for more than 90% of the prostate patients whose lateral dimensions are < 40 cm (Chen et al 2004a).

3) We also studied structure volume differences between CT and MRI on the AcQSim and Corvus systems, which led to small discrepancies in DVH curves for those structures with significant differences. These differences reflected the inherent uncertainties of target and structure delineation using different imaging modalities and different treatment planning systems. However, these DVH discrepancies will not be a problem when MRI is used alone for treatment planning since both structure contouring and treatment optimization will be performed using the same imaging modality (Chen et al 2004a, 2004b).

4) We evaluated MRI- and CT-based IMRT treatment optimization for plan consistency. Since both planning techniques will be used clinically and in different treatment protocols it is essential to ensure IMRT plans using both imaging modalities are consistent in terms of target coverage, dose conformity and normal tissue sparing. Our results showed that no clinically significant differences were found between MRI- and CT-based treatment plans using the same beam arrangements, dose constraints and optimization parameters (Chen et al 2004b).

5) We validated the dosimetry accuracy of MRI-based treatment planning by recomputing MRI-based IMRT plans using patient CT data and an IMRT QA phantom. The differences in dose distributions between MRI plans and the corresponding recomputed plans were generally within 3%/3mm. The differences in isocenter doses between MRI dose calculation and phantom measurements were within our clinical criterion of 4% (Chen et al 2004a).

<u>Validation and improvement of gradient distortion correction for MRI-based treatment planning</u>

The goal of our study is to provide “correct” pelvic images in which geometrical distortions are reduced to < 2 mm for target delineation and < 5 mm for external contour determination (which will be used to define patient geometry for dose calculation). This will require an assessment of the sources and magnitudes of the different contributions to distortions in images acquired using our 0.23 T MRI unit. In order to achieve the goal, first we quantified the residual distortions for 15 patients. The residual error was within 1 cm for patients with lateral dimensions < 40 cm. The values determined this way should have included the residual MRI distortions (both system related and object induced), differences in external contours due to patient setup between CT and MRI simulation, and the errors introduced by image fusion, which was estimated to be at the 2-3 mm level, which was achieved routinely in our clinic. The object induced effects are a result of both chemical shift and susceptibility effects due to the differences in the resonant frequency between fat and water and the magnetic field distortions introduced at tissue-air interfaces. The chemical shift artifacts and susceptibility distortion are larger on high-field MR units than on lower-field MR units. While chemical shift artifacts and susceptibility distortion can cause significant spatial misregistrations at high fields, their impact on

MRI at lower fields is substantially reduced. For fields below about 0.5 Tesla (T), imaging sequences that provide a sufficient signal to noise ratio keep geometric distortion due to either of these object-related effects below 1-2 pixels. This is achieved by defining a lower limit for the bandwidth of the readout gradient during image acquisition. One in vivo study has shown that with 0.2 T using a bandwidth readout gradient >100 Hz/pixel in frequency direction there is no artifact detected (Fransson et al 2001). In our clinical routine MR simulation we have chosen 154 Hz/pixel in the frequency encoding direction, therefore the effects caused by chemical and susceptibility are considered negligible. In this study we aimed on correction of the residual distortion after GDC correction due to system induced distortion. We performed phantom measurements to calibrate/quantify MRI distortion at different axial planes to derive distortion maps for phantom of different sizes. We have compared these maps with the measured distortion using real patients by comparisons with CT images. A point-by-point mapping technique was developed and computer software for improving the residual distortion using this method was also generated. Our results showed that by using this technique the residual distortion can be reduced to < 3 mm for patient lateral sizes up to 42 cm. A paper entitled "Investigation of MR Image Distortion for Radiotherapy Treatment Planning of Prostate Cancer" was published in Phys. Med. Biol (Chen et al 2006).

Investigation of the accuracy of a stereotactic body frame for patient immobilization

We performed MRI for different target localization and patient immobilization techniques to quantify the effect of prostate motion, and then to determine special treatment margins correspondingly. These will include alpha-cradle alone, and a stereotactic body frame from Radionics (Boston, MA). A Radionics Body Frame localizing system has been investigated at FCCC for accurate immobilization of patients undergoing stereotactic radiosurgery/therapy (SRS/SRT) using stereotactic IMRT optimization software and a micro multileaf collimator (mMLC) (Wang et al 2004a, 2004b).

The body system is a whole body fixation system using airflow modules, a vacuum system and fixation sheets. The treatment area is covered with a fixation sheet. When the vacuum system is turned on, the space around the patient between the vacuum cushion and the sheet is evacuated and the sheet is sucked against the vacuum cushion. The sheet nestles against the patient's body producing a uniform fixation to the body surface without causing impression.

To study the patient immobilization and target localization accuracy for this body system, we used the 0.23 T MRI to collect sequential axial and sagittal images of prostate patients. Each patient underwent one scan per week for 4 weeks. For this study, a fast image is required. The temporal resolution requires shorter than the breathing cycle (approximately 2.5 s) to measure respiration-related motion. We scanned the patients in both axial and sagittal planes respectively. T1 weighted FSE images with cines at 3 mm slice thickness with 60 images obtained every 2 seconds (TR/TE = 18/8 ms, FOV = 475 mm, Matrix = 128 x 256, ETL = 1, scan time 2 s) were obtained based on our pilot experiment. The prostate replacement was measured on MRI console in three dimensions on both axial and sagittal images and the absolute values of the displacement calculated based on pixel value. This experimental procedure was repeated without the vacuum body frame. The replacement of the prostate was compared between with and without the body frame. This can help us quantify the improvement with the body frame.

Task 2. Investigation of MRI-based treatment planning dose calculation

Evaluation of MRI-based prostate treatment planning dose calculation

We have focused on MR image distortion correction to further improve the accuracy of dose calculation for MR based treatment planning for prostate cancer (Chen et al 2006). We also used the Monte Carlo method to verify dosimetric accuracy and consistency for MR based IMRT treatment planning for prostate cancer (Chen et al 2007a). We summarize the results and conclusions of these studies as follows.

(1) We have focused on MR image distortion correction to further improve the accuracy of dose calculation for MR based treatment planning for prostate cancer. Our studies showed that, with our routine clinical 3-dimensinal fast spin echo sequences (3DFSE, 256 x 256, 1.855 mm pixel, TR = 140 ms, TE = 3000 ms, BW readout gradient > 100 Hz/pixel), there was no patient-induced distortions. Therefore, the residual machine specific geometrical distortions after the gradient distortion correction (GDC) could be quantified by phantom measurements and further reduced by our point-by-point correction technique. The effective field of views (FOV_{eff}) of the scanner were established based on the actual viewable areas with adequate geometric distortion corrections (ensuring < 5 mm distortion error). The effective FOV_{eff} for prostate imaging using a standard FOV of 48 cm has been expanded from 36 cm using the existing GDC software to 42 cm using the point-by-point distortion correction technique developed in this work. Our results indicated that, with the distortion maps established in this work, we could correct MR geometrical distortions for patients of lateral dimensions up to 42 cm. Significant improvement in dose calculation has been achieved based on a 1-2 cm improvement in patient external contour determination.

(2) We have performed the Monte Carlo method to verify dosimetric accuracy and consistency for MR based IMRT treatment planning for prostate cancer. The Monte Carlo code used in this work was MCSIM, which is an EGS4/PRESTA user code developed at Fox Chase Cancer Center (FCCC) (Ma et al 2002). The beam information was represented using a source model, which was built based on measured beam data (Jiang et al 2000, 2001; Yang et al 2004), and validated for Monte Carlo dose calculation for photon beams from our Siemens accelerators. During the calculation, the multi-leaf collimator leakage effect was taken into account when intensity maps were reconstructed from a plan. The accuracy of the dose calculation was better than 2% compared with measured data (Li et al 2000). For each patient, an RTP file from the Corvus treatment planning system that includes patient setup parameters and beam and leaf-sequence information was used for the Monte Carlo dose calculation. For the Monte Carlo simulation, the electron and photon energy cutoffs, ECUT and PCUT, for particle transport were set to 700 keV and 10 keV, respectively. The energy thresholds for δ ray production (AE) and for Bremsstrahlung production (AP) were also set to 700 keV and 10 keV, respectively. The maximum fractional energy loss per electron step (ESTEP) was set to 0.04 and the default parameters were used for the PRESTA algorithm. The patient geometry used for the Monte Carlo calculations was created based on both CT and MR data. The materials and mass densities of CT based geometries were converted from the CT numbers based on a piecewise linear conversion curve that was given by Ma et al (1999). Seventy million particle histories were used in the Monte Carlo simulations to achieve less than 0.5% statistical uncertainties to

the target dose for all the IMRT plans. Each photon was split 20 times to improve the simulation efficiency using the photon-splitting technique implemented in MCSIM.

(3) We have performed CT-based IMRT Monte Carlo dose calculations with and without heterogeneity corrections in order to investigate the heterogeneity effect caused by different beam angle arrangements. Based on the results, MR-based IMRT dose calculations were performed using either uniform density geometry or uniform density geometry with bulk electron density assigned to bony structures. For the plans with insignificant inhomogeneity effect, uniform geometries with water density were used in the MR-based dose calculation. For the plans that bony structure constitutes a large part of volume irradiated, uniform density geometry with bulk electron density assigned to bony structures was used in the MR-based dose calculation. Each IMRT plan was evaluated based on isodose distributions and dose volume histograms (DVHs) with CT-based or MR-based dose calculations. The clinical target volume (CTV) was chosen for the dose-volume comparison. Clinical quantities such as the mean dose, maximum and minimum dose received by the CTV and the critical structures were compared. The maximum dose was defined as the highest dose received by 1% of the target volume and the minimum dose was defined as the lowest dose received by 99% of the target volume, respectively. Other parameters such as the dose at the isocenter and the dose received by 95% and 5% of the CTV were also compared. The paired CT and MR data for any patients in this work were pre-processed to have the same pixel resolution. The internal contours of the targets and critical organs were contoured by oncologists on the fused CT-MR images. A special computer code was developed to convert the patient CT and MR image data from the DICOM format to geometries specially formatted for the MCSIM code.

Development of practical methods for heterogeneity correction for MRI-based dose calculation

Our preliminary results demonstrated that MR-based planning was equally good as CT-based planning for prostate cancer with homogeneity geometry in the dose calculation. The differences between CT and MR-based dose calculations came from the setup uncertainties in the CT and MR image acquisition (Chen et al 2005). For prostate cancer, the following beam arrangements were commonly used for routine treatment IMRT plans at Fox Chase Cancer Center: 1) one anterior, 2) two or four anterior oblique, 3) two lateral and 4) two or four posterior oblique beams. The couch angles were set as zero (i.e. coplanar beam arrangements). Our results showed insignificant differences in the clinical quantities between MR-based dose calculations with uniform water equivalent geometry and CT-based dose calculations with heterogeneity correction. The maximum differences were less than 4% and the averaged differences over the 10 IMRT plans were less then 1.6% for all the quantities in the comparison, indicating that the uniform geometry was a good approach with our commonly used beam arrangements. These results were consistent with previous findings (Chen at al 2004 and Yang et al 2004).

However, for some clinical cases non-coplanar beam arrangements were needed to achieve better target dose coverage and rectal sparing. Our results showed that with non-coplanar beam arrangements more than 10% differences between plans with and without heterogeneity correction were found in the single beam calculations for the beam going through a large amount of pelvic bones. To utilize MR-based planning for the treatment with large amount of pelvic bones irradiated, heterogeneity corrections must be taking into account and a bulk-density can be assigned to bony structures as proposed by this project since there is no point-to-point correlation between MR signal intensities and

electron densities of the materials imaged (Lee and Bollet 2003, Chen et al 2004b). Various bulk-densities (between 1.5 and 2.2 g/cm^3) were assigned to the femurs and femoral heads in this work. Our results showed that 1.8g/cm^3 is the optimal value for the bulk-density assignment.

For those beams with gantry/table angles as 275/340, 85/20 and 85/0, the differences in the average target doses were decreased from about 10% with uniform water equivalent geometry to about 3% or less after assigning 1.8g/cm^3 bulk density to femurs and femoral heads. The changes in DVHs using CT data with 1.8g/cm^3 bulk density for the femurs and femoral heads also confirmed our findings.

Task 3. Development of practical procedures for clinical implementation of MRI simulation

Creation of MR-based Digitally Reconstructed Radiographs (DRRs)

We have focused on developing a technique to create MR-based digitally reconstructed radiographs (DRR) for prostate IMRT patient setup when MR-based treatment planning is applied clinically. A paper entitled "MRI-Based Treatment Planning for Prostate IMRT: Creation of Digitally Reconstructed Radiographs (DRR)" was published in Int. J. Radiat. Oncol. Biol. Phys (Chen et al 2007b). We studied MR image distortion corrections to further improve the accuracy of dose calculation for MR based treatment planning for prostate cancer. A paper entitled "Investigation of MR image distortion for radiotherapy treatment planning of prostate cancer" has been published in *Physics in Medicine and Biology* (Chen et al 2006). We also used the Monte Carlo method to further verify dosimetric accuracy and consistency for MR based IMRT treatment planning for prostate cancer. A short paper entitled "Monte Carlo dose verification of MR image based IMRT treatment planning for prostate cancer" has been submitted to XVth Intenational Conference on the Use of Computers in Radiation Therapy (ICCR. Toronto, Jun 2007) (Chen et al 2007b). The two manuscripts together with the published paper are also attached to this report. We summarize the results and conclusions of these studies as follows.

Our previous studies demonstrated that MRI-based treatment planning meets the dosimetric accuracy for prostate IMRT and it is adequate to use unity density in treatment planning dose calculation with co-planar beam arrangements for prostate cancer treatment after correction of MRI distortions (Chen et al 2004a, 2004b). With CT-based treatment planning, the CT-based DRRs are routinely used for patient treatment set-up verification by comparing with portal film or electronic portal imaging devices (EPID). With MR-based treatment planning, Since MRI-derived DRRs do not provide enough bony structure information and therefore cannot be used directly for checking patient positions. To overcome this problem, we have developed a technique to create MR-based DRRs for patient initial setup for routine clinical applications of MR-based treatment planning for prostate patient treated with IMRT. Twenty prostate patients' CT and MR images were used for the study. CT and MR images were fused. The pelvic bony structures including femoral heads, pubic rami, ischium and ischial tuberosity that are relevant for routine clinical patient setup were manually contoured on axial MR images using the AcQsim planning system. The contoured bony structures were then assigned a bulk density of 2.0 g/cm^3. The MRI based DRRs were generated. The accuracy of the MR based DDRs was quantitatively evaluated by comparing MR-based DRRs with CT-based DRRs for these patients. For each patient 8 measuring points on both coronal and sagittal DRRs were used for quantitative evaluation. Our results showed that the maximum difference in the mean values of these measurement points is 1.3 and the maximum difference in absolute positions is within 3 mm for the 20 patients investigated. MR-based DRRs are comparable to CT-based DRRs for prostate IMRT. This technique

has been used, in combination with the BAT/in-room CT daily target localization technique, for the clinical implementation of MRI-based treatment planning for prostate IMRT at FCCC.

Development of guidelines for MRI-based treatment planning dose calculation

We investigated the effect of MRI residual distortion after gradient distortion correction (GDC) on IMRT treatment planning and dosimetry accuracy. The residual distortion errors are less than 1 cm and will have negligible clinical impact for more than 90% of the prostate patients whose lateral dimensions are <40 cm. We have investigated on MR image distortion correction to further improve the accuracy of dose calculation for MR based treatment planning for prostate cancer. Our studies showed that, with our routine clinical 3-dimensinal fast spin echo sequences (3DFSE, 256 x 256, 1.855 mm pixel, TR = 140 ms, TE = 3000 ms, BW readout gradient > 100 Hz/pixel), there was no patient-induced susceptibility distortions. Therefore, the residual machine specific geometrical distortions after the GDC could be quantified by phantom measurements and further reduced by our point-by-point correction technique. The effective field of view (FOV_{eff}) of the scanner was established based on the actual viewable areas with adequate geometric distortion corrections (ensuring < 5 mm distortion error). The effective FOV_{eff} for prostate imaging using a standard FOV of 48 cm has been expanded from 36 cm using the existing GDC software to 42 cm using the point-by-point distortion correction technique developed in this work. Our results indicated that, with the distortion maps established in this work, we could correct MR geometrical distortions for patients of lateral dimensions up to 42 cm. Significant improvement in dose calculation has been achieved based on a 1-2 cm improvement in patient external contour determination (Chen et al 2006).

Our previous study results showed that no clinically significant differences in dose calculations were found between MRI- and CT-based treatment plans using the same beam arrangements, dose constraints and optimization parameters. We also validated the dosimetry accuracy of MRI-based treatment planning by recomputing MRI-based IMRT plans using patient CT data and an IMRT QA phantom. The differences in dose distributions between MRI plans and the corresponding recomputed plans were generally within 3%/3mm. The differences in isocenter doses between MRI dose calculation and phantom measurements were within our clinical criterion of 4%.

This year we focused on the Monte Carlo method to further verify dosimetric accuracy and consistency for MR based IMRT treatment planning for prostate cancer. The Monte Carlo code used in this work was MCSIM, which is an EGS4/PRESTA user code developed at FCCC (Ma et al 2002). We have performed CT-based IMRT Monte Carlo dose calculations with and without heterogeneity corrections in order to investigate the heterogeneity effect caused by different beam angle arrangements. Based on the results, MR-based IMRT dose calculations were performed using either uniform density geometry or uniform density geometry with bulk electron density assigned to bony structures. For the plans with insignificant inhomogeneity effect, uniform geometries with water density were used in the MR-based dose calculation. For the plans that bony structure constitutes a large part of volume irradiated, uniform density geometry with bulk electron density assigned to bony structures was used in the MR-based dose calculation. Each IMRT plan was evaluated based on isodose distributions and dose volume histograms (DVHs) with CT-based or MR-based dose calculations. The clinical target volume (CTV) was chosen for the dose-volume comparison. Clinical quantities such as the mean dose, maximum and minimum dose received by the CTV and the critical structures were compared. The maximum dose was defined as the highest dose received by 1% of the target volume and the minimum dose was defined as the lowest dose received by 99% of the target volume, respectively. Other parameters such

as the dose at the isocenter and the dose received by 95% and 5% of the CTV were also compared. The paired CT and MR data for any patients in this work were pre-processed to have the same pixel resolution. The internal contours of the targets and critical organs were contoured by oncologists on the fused CT-MR images. A special computer code was developed to convert the patient CT and MR image data from the DICOM format to geometries specially formatted for the MCSIM code (Chen et al 2007).

Our results showed that the differences in dose calculations between CT data (with heterogeneity correction) and MR data (with uniform water equivalent geometry) were about 3% or less and less than 2% in the mean values for the 10 plans with beams arranged in the axial plane. For MR-based calculations (with homogeneous geometry), our results demonstrated that the differences between MR-based calculations and CT-based calculations (without heterogeneity correction) were less than 2% for the individual patients and about 1% in the mean values, which proved that MR-based IMRT plans can be used to replace CT-based planning clinically. The 1% - 2% differences in dose calculations were mainly caused by the setup uncertainties of the two imaging modalities if geometrical distortions on the MR images were corrected to less than 3 mm. For treatments in which relatively large amount of bones are irradiated, MR-based treatment planning with homogeneous geometry would not be appropriate because of the excessive attenuation of the photon beams passing through bony structures. However, by assigning bulk densities to the bony structures especially for the femurs and femoral heads, the dose differences could be reduced to less than 3%. The bulk density assigned to the femurs that gave the best fits to CT-based calculations with heterogeneity correction was 1.8g/cm^3 in our simulations (Chen et al 2007).

Development of quality assurance programs for MRI simulation for prostate cancer treatment

We have established a practical procedure for MR-based treatment planning. 1) An optimal MR protocol was first developed for contouring the target and critical structures. 2) We investigated the effect of MRI residual distortion after the GDC on IMRT treatment planning and dosimetry accuracy. The residual distortion errors are less than 1 cm and will have negligible clinical impact for more than 90% of the prostate patients whose lateral dimensions are <40 cm. For patients whose lateral dimensions are > 40 cm we will use the point-by-point distortion correction technique developed in this work. Our results indicated that, with the distortion maps established in this work, we could correct MR geometrical distortions for patients of lateral dimensions up to 42 cm. 3) We have investigated optimal fiducial markers for MRI simulation. We have introduced a new donut-shaped marker to improve isocenter definition (IZI medical Product, Baltimore, Maryland 21244). The marker contains iodine with a 1.5 cm outer diameter and a 4 mm inner diameter. The centers of the markers can be detected clearly on one MR slice to define the treatment isocenter. To implement MRI simulation, a set of trackable lasers has been installed in the MR room for patient setup and isocenter determination. 4) We have demonstrated that MRI-based treatment planning meets the dosimetric accuracy for prostate IMRT and it is adequate to use unity density in treatment planning dose calculation with co-planar beams for prostate cancer treatment after MRI distortion corrections (Chen et al 2004a, 2004b), 5) We have developed practical methods for heterogeneity correction for MRI-based dose calculations (Chen et al 2007). 6) finally MRI-based DRRs are used during initial treatment setup together with CT-on-rails/cone-beam CT//BAT and later on as a backup for these imaging systems if the systems are down. We investigated the creation of MRI-based DRRs to facilitate initial patient setup. CT-based DRRs are routinely used for patient treatment setup verification by comparing with portal film or electronic portal imaging devices (EPID). However, directly MRI-derived DRRs do not provide enough bony

structure information and therefore cannot be used directly for checking patient positions. To overcome this problem, a practical method to derive MRI-based DRRs for IMRT prostate patient setup has been developed. The relevant bony structures on MRI including pubic symphysis, femoral heads and acetabulum are contoured and assigned a bulk density of 2.0 g/cm^3. The bony structures are then clearly shown on the MRI-derived DRRs and can be used for patient treatment setup verification. The accuracy of this method has been verified by comparing with CT derived DRRs and the agreement between the two methods are estimated to be 2-3 mm based on 20 patients investigated (Chen et al 2007).

Key Research Accomplishments

We have accomplished the following tasks:

- We have verified the dosimetry accuracy of prostate treatment planning using homogeneous patient geometry by doing dose calculations on CT with and without heterogeneity correction for 15 patients.

- We have evaluated the dosimetric accuracy of CT- and MRI-based treatment planning using homogeneous geometry using AcQSim planning system.

- We have investigated the effect of MRI residual distortion after GDC on IMRT treatment planning and dosimetry accuracy.

- We have studied structure volume differences between CT and MRI on the AcQSim and Corvus system.

- We have evaluated MRI- and CT-based IMRT treatment optimization for plan consistency.

- We have validated the dosimetry accuracy of MRI-based treatment planning by recomputing MRI-based IMRT plans using patient CT data and an IMRT QA phantom.

- We have developed a point-by point distortion correction technique to correct MR geometrical residual distortions with the use of the gradient distortion correction (GDC) software.

- We have developed practical methods for heterogeneity correction for MRI-based dose calculation in inhomogeneous patient anatomy.

- We have used the Monte Carlo method to validate the dose accuracy and consistency for MR-based treatment planning of prostate cancer.

- The dose accuracy for MR-based treatment planning of prostate cancer has been validated using the Monte Carlo method and demonstrated consistent results.

- A practical method for heterogeneity correction for MRI-based dose calculation in inhomogeneous patient anatomy has been developed.

- A practical technique to create MR-based DRRs for prostate IMRT has been developed that can be used for patient setup when MR-based treatment planning is applied clinically.

Reportable Outcomes and Bibliography

Peer-reviewed papers resulting from or supported in part by this grant:

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- **Chen L.** Magnetic resonance has proven useful in radiation therapy simulation and treatment planning for prostate intensity-modulated radiation therapy *Advance for Imaging and Oncology* 14 57-58 (2004).

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- Y. Cao and **L. Chen**. MRI in Radiation Treatment Planning and Assessment. In: Integrating New Technologies into the Clinic: Monte Carlo and Image-Guided Radiation Therapy (ed. Bruce H. Curran, James M. Balter, and Indrin J. Chetty). Medical Physics Publishing (Madison, WI), 2006, pp401-424.

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1. **Chen L.** Cancer treatment with MRI-guided high intensity focused ultrasound. Medical Physics, 2007; 34: 2588.
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Proposal Title: MR Guided Pulsed High Intensity Focused Ultrasound Enhancement of Gene Therapy Combined with Androgen Deprivation and Radiotherapy for Prostate Cancer Treatment (2008-2011)

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Proposal Title: MR Guided Pulsed High Intensity Focused Ultrasound Enhancement of Docetaxel Combined with Radiotherapy for Prostate Cancer Treatment (2008)

- PI, Fox Cancer Center Seed Grand: **pending**

Proposal Title: MR Guided High-Intensity Focused Ultrasound for Enhancement of Chemo-Radiotherapy of Prostate Cancer

Conclusions

We have successfully performed the tasks scheduled in the "Statement of Work". We have confirmed that treatment planning dose calculations using MRI-derived homogenous geometry are adequate for patient sizes within 38 cm after MR image distortion is corrected using the GDC software. We have investigated the effect of MRI residual distortion after GDC on IMRT treatment planning and dosimetry accuracy. We have evaluated MRI- and CT-based IMRT treatment optimization for plan consistency. We have validated the dosimetry accuracy of MRI-based treatment planning by recomputing MRI-based IMRT plans using patient CT data and an IMRT QA phantom. We have developed a point-by-point distortion correction technique to correct the residual MRI distortions after the GDC. We have performed Mote Carlo dose calculations using MRI-derived homogenous geometry with heterogeneity corrections. We have developed a practical method of dose calculation for MR-based treatment planning in heterogeneous patient anatomy. We have developed a practical technique to create MR-based DRRs for prostate IMRT that can be used for patient setup when MR-based treatment planning is applied clinically. We have developed guidelines for MRI-based treatment planning dose calculation and quality assurance programs for MRI simulation for prostate cancer treatment. We have successfully implemented MR imaging based treatment planning clinically at FCCC.

Note on Human Subject Protection Approval

We have an approved IRB (IRB# 04-848) by both Fox Chase Cancer Center and DOD for this project.

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